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**SENSORY ADAPTATION EFFECTS FOLLOWING EXPOSURE TO A VIRTUAL ENVIRONMENT**

by

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The Navy's operational manual 3710.7Q states that flight personnel exhibiting symptoms of simulator exposure must abstain from same-day flying duties, and those who have a history of simulator sickness must be removed from the flight schedule for at least 24 hours following simulator exposure. The cause of simulator sickness is currently unknown, but researchers hypothesize it results from a sensory-input mismatch between the visual and vestibular sensory organs. Previous simulator-sickness studies used questionnaires to measure sickness severity; however this is a crude measure with inconsistent findings. The goal of this study was to determine quantitatively whether low-level sensory functions are disrupted in a virtual environment, and determine whether long-term simulator exposure causes sensory adaptation. In order to answer these questions, smooth pursuit parameters, perceptual distance estimation, horizontal eye movements, and relative comfort level were measured before and after immersion in four different display formats. This study failed to find any statistically significant changes in low-level vision functions. However, as with virtually every other study done on simulator sickness, this study did find statistically significant differences in comfort level (as measured with the Simulator Sickness Questionnaire) when using a head-mounted display and a 3-panel display as compared to a control condition.

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# SENSORY ADAPTATION EFFECTS FOLLOWING EXPOSURE TO A VIRTUAL ENVIRONMENT


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# ABSTRACT

The Navy's operational manual 3710.7Q states that flight personnel exhibiting symptoms of simulator exposure must abstain from same-day flying duties, and those who have a history of simulator sickness must be removed from the flight schedule for at least 24 hours following simulator exposure. The cause of simulator sickness is currently unknown, but researchers hypothesize it results from a sensory-input mismatch between the visual and vestibular sensory organs. Previous simulator-sickness studies used questionnaires to measure sickness severity; however, this is a crude measure with inconsistent findings. The goal of this study was to determine quantitatively whether low-level sensory functions are disrupted in a virtual environment, and determine whether long-term simulator exposure causes sensory adaptation. In order to answer these questions, smooth pursuit parameters, perceptual distance estimation, horizontal eye movements, and relative comfort level were measured before and after immersion in four different display formats. This study failed to find any statistically significant changes in low-level vision functions. However, as with virtually every other study done on simulator sickness, this study did find statistically significant differences in comfort level (as measured with the Simulator Sickness Questionnaire) when using a head-mounted display and a 3-panel display as compared to a control condition.

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## EXECUTIVE SUMMARY

Over the past decade, the military budget has decreased despite an increase in operational commitments. As a result, the military services have had fewer dollars to dedicate towards quality hands-on training. The Department of Defense has therefore attempted to offset the loss of realistic hands-on training with devices that mimic the real world. For example, the Department of Defense's 1996 Defense Technology Area Plan cites as one of its technical challenges "the ability to provide a truly interactive virtual reality depiction of the situation with human immersion." Clearly, virtual environment (VE) training will continue to grow in importance for the military.

A significant percentage of users report adverse physiological effects from prolonged VE exposure. The US Navy recognizes that simulator sickness is a problem for pilots. The Navy's operational manual (OPNAVINST 3710.7Q, 1995) states that flight personnel exhibiting symptoms of simulator exposure must abstain from same-day flying duties and those who have a history of simulator sickness must be removed from the flight schedule for at least 24 hours following simulator exposure. If the military plans to allocate more training time to VE devices, then mission planners must become knowledgeable about the occurrence of VE sickness and the potential for some individuals to be particularly susceptible to simulator sickness symptoms.

The goal of this study was to determine quantitatively whether low-level sensory functions are disrupted in a virtual environment, and determine whether long-term simulator exposure causes sensory adaptation. In order to answer these questions, smooth pursuit parameters, perceptual distance estimation, horizontal eye movements,

and relative comfort level were measured before and after immersion in four different display formats.

This study failed to find any statistically significant changes in low-level vision functions. This may be attributed to some of the technical aspects and difficulties of this study and does not rule out the fact that these parameter may indeed be affected by exposure to Virtual Environments. On the other hand, as with virtually every other study done on simulator sickness, this study did find statistically significant differences in comfort level (as measured with the Simulator Sickness Questionnaire) between the head-mounted display group and both the control and CRT groups, as well as between the 3-panel display group, and both the control and CRT groups.

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# I. INTRODUCTION

## A. THE PROBLEM

Over the past decade, the military budget has decreased despite an increase in operational commitments. As a result, the military services have had fewer dollars to dedicate towards quality hands-on training. To meet this training deficiency, the Department of Defense has authorized the use of training simulators to help maintain military readiness (Department of Defense Directive 1430.13). The military had already relied on training devices to assist users in the early stages of task learning. The purpose of these devices was to assist the user's basic understanding of a particular system, with the majority of learning and a more complete formulation of motor skills to be accomplished during hands-on operational training. Although simulators have many positive attributes, system operators within the military have expressed concern over the growing proportion of time spent using training devices versus the actual system in the past several years. Operators complain that the loss of realistic hands-on training will have a negative impact on military readiness and operational safety (North, 1997; Sullivan, 1998). The Department of Defense has attempted to offset the loss of realistic hands-on training with devices that mimic the real world. The Department of Defense's 1996 Defense Technology Area Plan cites as one of its technical challenges "the ability to provide a truly interactive virtual reality depiction of the situation with human immersion." Clearly, virtual environment (VE) use will continue to grow in importance for the military.

However, a significant percentage of users report adverse physiological effects from prolonged VE exposure. These effects are usually reported as symptoms that resemble motion sickness. If these symptoms result from interactions with the simulator but would not have occurred with the actual device (car, aircraft, etc..), the condition is referred to as "simulator sickness." The US Navy recognizes that simulator sickness is a problem for pilots. Section 8.3.2.17 of OPNAVINST 3710.7Q states the following:

> Simulator exposure can cause perceptual sensory changes that may compromise safety... Symptoms of simulator sickness may occur during simulator flight and last several hours after exposure... Preliminary data suggest that more experienced flight personnel may be at greater risk, as well as individuals who are new to the simulator. Flight personnel exhibiting symptoms of simulator exposure should abstain from same-day flying duties. Individuals who have experienced simulator sickness in the past have a greater probability of recurrence and should not be scheduled to fly for 24 hours following simulator exposure. Adaptation does occur over time.

If the military allocates more of the users' training time to VE devices, then mission planners must be informed about the occurrence of VE sickness and the potential for some individuals to be particularly susceptible to simulator-sickness symptoms. The purpose of this study is to determine quantitatively whether low-level sensory functions are disrupted in a virtual environment, and determine whether long-term simulator exposure causes sensory adaptation. The following sections will provide an understanding of the key elements pertinent to this study.

## B. VIRTUAL ENVIRONMENTS

In order to understand the potential problems associated with virtual environments, it is necessary to understand what they are and how they are used. It is

generally accepted that VEs have the following attributes: 1) they are generated by a computer; 2) participants experience the environment in three dimensions; 3) participants have a sense of presence in the environment; 4) participants can navigate through the environment; 5) behavior of objects in the environment match their behavior in real life; and 6) interaction is in real time (Wilson, 1996). Virtual environments are therefore used to create experiences that appear and behave realistically, consistently, and coherently, and allow the user both to perform better than he could otherwise and then to relate that experience to the real world (Wilson, 1996). However, the physiological discomfort experienced by some users of VE can interfere with any positive transfer of training and in some instances can lead to poor habits developed through attempts to overcome the discomfort.

## C. MOTION SICKNESS

Motion sickness is a general term for a collection of generally adverse symptoms caused by exposure to abrupt, periodic, or unnatural accelerations. A variety of species, including chimpanzees, monkeys, horses, cows, birds, and fish exhibit signs of motion sickness (McCauley and Sharkey, 1992). Overt signs include sweating, increased salivation, and vomiting; however, drowsiness, dizziness, and nausea are the most reported symptoms. Other signs include changes in cardiovascular, respiratory, gastrointestinal, biochemical, and/or temperature regulation functions (Reason and Brand, 1978). Studies have shown that only people with nonfunctional vestibular systems are completely immune to motion sickness (McCauley and Sharkey, 1992). The rest of the

population experiences varying degrees depending upon individual characteristics and the nature of the environment they are in (very rough sea, airplane, car, etc.). The consequences of motion sickness can be decreased spontaneity, carelessness, and lack of coordination, particularly in manual control (Kennedy, Frank and McCauley, 1985).

## D. SIMULATOR SICKNESS

Although the symptoms of simulator sickness are similar to those of motion-induced sickness, they tend to be less severe, of lower incidence, and to originate from elements of the visual display and visuo-vestiblular interaction atypical of conditions that induce motion sickness (Kennedy, Lane, Berbaum and Lilienthal, 1993). The majority of the initial research on simulator sickness attempted to assess the user's physiological comfort level during or immediately following exposure to a virtual environment. In order to do this researchers used the Simulator Sickness Questionnaire (SSQ), adapted from the Pensacola Motion Sickness Questionnaire, to measure physiological discomfort.

Kennedy and Fowlkes (1992) refer to simulator sickness as polygenic (having many distinct sources) and polysymptomatic (having many symptoms). The most widely accepted explanation for the cause of simulator sickness is a sensory input mismatch, between the visual and vestibular sensory organs (the set of canals and tubes in the inner ear that give a sense of orientation and acceleration), referred to as "cue conflict." In a virtual environment, the conflict is thought to be between the visual and vestibular senses (Kolasinski, 1995; Kennedy et al., 1985). For example, the visual system may perceive that the body is moving rapidly, while the vestibular system perceives the body to be

stationary. This sensation can occur either with little to no physical motion or with physical motion, if the physical and visual cues are not synchronized (Kolasinski, 1995). Havron and Butler (1957) found that a large percentage of people reported adverse reaction after prolonged exposure to a helicopter simulator. Subsequent studies (Kennedy, Frank and McCauley, 1985; Kennedy, Lilienthal, Berbaum, Baltzley and McCauley, 1989; Baltzley, Kennedy, Berbaum, Lilienthal and Gower, 1989; Ungs, 1988) confirmed Havron and Butler's findings and concluded that simulator sickness symptomatically resembles motion sickness and other forms of distress which occur after exposure to altered or rearranged sensory information.

Factors that may contribute to cue conflict and thus simulator sickness can be divided into three groups (Kolasinski, 1995). The first group consists of technical characteristics related to the virtual environment. Examples include binocular viewing (slightly different images presented to each eye) which some studies suggest results in increased sickness (Rushton, Mon-Williams and Wann, 1994). A wider field of view (FOV) has also been demonstrated to increase the incidence and severity of sickness (Kennedy et al., 1989). Screen flicker, which induces eye fatigue, also appears to be associated with simulator sickness (Kolasinski, 1995; Kennedy, 1996).

The second group consists of factors relate to the individual. Examples of this include age, gender, and simulator experience. Reason and Brand (1978) found that motion sickness susceptibility is generally greatest between ages two and 12. After 12 susceptibility begins to decline until it is typically nonexistent after age 50. Kennedy, Lanham, Massey, Drexler, and Lilienthal (1995) found that women show a higher

incidence of simulator sickness than do men. Also, increased simulator experience may decrease the signs of simulator sickness. Uliano, Lanbert, Kennedy and Sheppard (1986) found that pilots who experienced sickness in initial simulator sessions were able to adapt rapidly to the simulator in subsequent sessions, and therefore experienced fewer sickness symptoms over time.

The third group consists of factors related to the task or tasks performed in the virtual environment. These include the degree of control a user has (controlling allows for anticipation of future movements), which may help reduce cue conflict. Sickness rates have been shown to be lower for persons with higher degrees of control (Kolasinski, 1995). High rates of linear or rotational acceleration may also cause sickness (McCauley, Sharkey, 1992). Finally, unusual movements in the virtual environment may also induce sickness (McCauley and Sharkey, 1992).

## E. POST EFFECTS

Several studies have shown that virtual environments not only cause physiological discomfort, but also adverse post-effects in the user (Kennedy, Lanham, Drexler, Massey and Lilienthal, 1995; Baltzley et al., 1989; Ungs 1989; Regan and Price, 1994). Using the SSQ, Regan and Price (1994) found that 61 percent of their subjects reported some symptoms of malaise ten minutes after leaving the virtual environment. These symptoms ranged from dizziness, stomach awareness, headaches, eyestrain and lightheadedness, to severe nausea.

Similarly, Baltzley and Kennedy (1989) measured over 700 Navy and Army pilots' physiological comfort rating scores after being exposed to a flight simulator. They found the following: 45 percent of the pilots experienced simulator sickness symptoms immediately after exposure; 25 percent experienced symptoms one hour later; and 8 percent six hours later. Ungs (1989) found that 4.6 percent of U.S. Coast Guard pilots surveyed reported experiencing symptoms 24 hours or more after leaving a flight simulator. In addition, 1.5 percent of the pilots were removed from flight status for several days due to the adverse effects of simulator exposure.

## F. ADAPTATION

Held (1968) and Welch (1978) examined perceptual adaptation caused by radical transformation of vision, mainly with the use of prisms to distort a subject's view. These prisms inverted the observer's visual scene. After a few days, subjects could perform simple tasks under these distorted conditions, such as eating with utensils. After a few weeks, subjects were able to perform complex motor tasks such as riding a bicycle. Neurophysiologists have demonstrated analogous effects for animals which have lost digits. Studies have shown that cortical neurons that were once mapped to a missing digit will migrate to a neighboring digit (Julesz and Kovacs, 1995). Perhaps the cortical neurons of Held and Welch's subjects adapted to the new environment. Interestingly, when the subjects removed the prisms, the world was perceived as upside-down again, but the effect rapidly dissipated. Perhaps users experience similar physiological changes from prolonged VE exposure. The virtual environment presents to the user a distorted

scene similar to that from Held and Welch's prisms. Furthermore, the qualitative VE studies found that subjects report the most discomfort immediately after exposure with the effects quickly dissipating.

## G. ADAPTATION TO VIRTUAL ENVIRONMENTS

The majority of the research done on simulator sickness is based on data from subjective questionnaires. In the attempt to gain objective information about the potential physiological changes taking place in the virtual environment, two principal types of studies have been conducted. One type has attempted to quantify a change in postural instability (Kennedy and Stanney, 1996; Kennedy, Berbaum and Lilienthal, 1997), and the other has measured various changes in visual or visual-motor systems (Fowlkes, Kennedy, Hettinger and Harm 1993; Neveu, Blackmon and Stark, 1998; Biocca and Rolland, 1998; Werkhoven and Groen, 1997; Peli, 1998; Wann, Rushton and Mon-Williams, 1995).

In investigating the vision system, one of the most widely researched fields is that of accommodation and convergence. Accommodation is the eye's ability to focus at different distances; it is accomplished by a low-level visual process that changes the shape of the lens. Convergence, on the other hand, is the ability of the eyes to turn inward together in order to see an object singularly. In viewing the real world, the eyes accommodate and converge for the same distance. In viewing a virtual environment, the view screening is at one distance from the eyes and the image generated appears at another, thus creating a mismatch between accommodation and convergence (Wilson,

1996). Furthermore, Fowlkes, Kennedy, Hettinger, and Harm (1993) found a relationship between shifts in dark-focus accommodation (the point of focus in the absence of effective visual stimulation) and simulator sickness. However, other studies of various accommodation parameters (Neveu, Blackmon and Stark, 1998) have been inconclusive.

Additional research has discovered other effects on visual functions. For example, Mon-Williams, Wann, and Rushton (1993) found evidence of changes in visual functions after using a stereoscopic (binocular) head-mounted display (HMD) for a period of 10 minutes. When a bi-ocular display (the same image is presented to both eyes) was used in a different study by the same researchers (Rushton, et al., 1994) the results were not repeated. There is danger, however, in comparing these two studies as some have attempted to do. The bi-ocular study (Rushton, et al., 1994) used a larger sample size with different subjects, adjusted for inter-pupillary distance, and used newer-generation equipment with higher resolution. Therefore the differences found cannot be attributed solely to the mode in which the image was displayed, but may have been affected by the other conditions that varied between the two studies (higher resolution equipment, etc..)

In a similar study, Peli (1998) measured functional changes in binocular vision, accommodation, and resolution after 30 minutes of HMD use in both the monoscopic and stereoscopic mode compared to desk-top CRT use. He found no statistically significant changes in the visual system. It is the use of this control measure that differentiates his study from Mon-Williams, et al., 1993. As with other studies (Mon-Williams et al., 1993), Peli (1998) did find significant changes in the subjective comfort level of the users with the stereoscopic HMD versus the CRT, and concluded that discomfort and eyestrain

of a vague nature are associated with head-mounted display use. It is important to note that a lack of a significant effect for one of the quantitative variables does not completely rule out the possibility that a physiological change occurred after simulator exposure.

Another vision parameter that has been studied to some extent in relation to simulator sickness is the vestibulo-ocular reflex (VOR). The VOR is an involuntary eye-movement reflex that functions to keep images stabilized on the retina during movement of the head, thus allowing for sight during movement. When the head begins to move, the vestibular apparatus senses this movement and sends direction and rate information to the oculomotor system. The oculomotor system then responds by moving the eyes at the same rate in the opposite direction to keep the visual image stabilized on the retina (Draper, 1996).

The VOR has the ability to adapt to stimuli that create a mismatch between a given VOR setting and what is required to keep an image stabilized on the retina (Robinson, 1981). This mismatch may be generated internally, due to effects of age, disease, or trauma, or it may be created externally, as would happen when putting on a scuba mask (Draper, 1998). Whether caused by internal or external conditions, the VOR is capable of adapting its *gain* (slow-phase eye velocity divided by head velocity) and *phase* (relative timing of head and eye movement) settings in order to stabilize the image. Draper (1998) found both VOR gain and phase adaptation consistently resulted from exposure to virtual environments.

## H. EYE MOVEMENTS

The VOR is only one of five major types of eye movement (VOR, optokinetic, saccade, smooth pursuit, and vergence) that work together to bring targets into the fovea (the small rodless area of the retina that affords acute vision) and keep them there. Optokinetic and smooth pursuit are visual tracking eye movements that work in conjunction with the VOR to maintain a stable image in the retina.

The optokinetic reflex or optokinetic nystagmus (OKN) uses visual input to maintain a stable retinal image, whereas the VOR uses vestibular input for this same purpose. If an image slips in the retina, the optokinetic reflex moves the eye with equal gain in the opposite direction of the image flow. This movement continues until the eyes near the edge of their orbit, at which point the eyes rapidly reverse direction and the process repeats itself. The slow movement of the eyes in the direction of the stimulus is referred to as the *slow phase* of the nystagmus, while the rapid movement in the opposite direction is the *fast phase*. The VOR and OKN work in concert to provide optimal image stabilization during movement.

Although the VOR can be elicited in a dark room with only vestibular input, visual input is necessary for VOR adaptation. It is this same visual input that the OKN uses. It follows that if a mismatch in conditions can create a change in VOR parameters, perhaps this same mismatch causes adaptation in the OKN.

Similar to the OKN, smooth pursuit eye movement uses visual input to generate eye movement. However, this movement functions to keep only the image on the fovea stabilized (Robinson, 1981). Smooth pursuit uses visual information of the image in the

fovea to calculate its velocity so that the eyes can accurately track a moving image, thus giving the ability to maintain a clear picture of a small target moving across a complex background. The adaptability of the smooth pursuit system has been demonstrated by adding a portion of the recorded eye motion onto target motion (Donkelaar, Gauthier, Blouin and Vercher, 1996). After repeated exposure to these conditions, subsequent smooth-pursuit responses to a constant velocity target were greatly enhanced. (Donkelaar, et al., 1996).

Another area of interest in perceptual adaptation is distance estimation. The ability to estimate distance accurately is an important component of navigation and is accomplished through the operation of several different perceptual cues gathered from the environment (Wickens, 1992). These cues include objected centered cues, such as texture and linear perspective, and observer centered cues like binocular disparity, convergence and accommodation (Wickens, 1992).

Distances estimations can be measured as *perceived distance* or *traversed distance*. Perceived distance is the observer's judgement of the distance between himself and a stationary or moving object, whereas traversed distance is the observer's judgement of the length of the route he traveled. Distance estimation has been studied for a number of years with the majority of the studies finding that people are not very accurate at estimating perceived distances (Witmer and Kline, 1998). The limited number of studies (Kline and Witmer, 1996; Lampton, Singer, McDonald and Bliss, 1995; Witmer and Kline, 1998) investigating distance estimation in virtual environments have found that

people are even less accurate there than in the real world. This is not surprising since the necessary perceptual cues are different in a virtual environment than in the real world.

## I. SUMMARY

The fact that people experience motion-sickness-like symptoms in a virtual environment suggests that inconsistent information is received by the different senses (Kolasinski, 1995). It has been demonstrated that when erroneous information is presented to the brain, the latter adapts in an attempt to continue functioning (Held, 1965; Welch, 1978). Perhaps observers within a virtual environment experience some sort of perceptual adaptation. It is hypothesized that immersion in a virtual environment causes adaptation in low-level vision functions.

In order to test this hypothesis, three questions will be asked. First, is there a change in the optokinetic nystagmus after immersion in a virtual environment? A change in VOR parameters has been shown after immersion in a VE (Draper, 1998). Because of the strong relationship between the VOR and OKN it is expected similar adaptation will be seen.

Second, is the initiation and maintenance of smooth-pursuit eye movement degraded after immersion in a virtual environment? Again, because of the relationship between these visual functions and the mismatch in visual-vestibular input, it is possible that the smooth pursuit function adapts in the virtual environment as well.

Third, is the ability to perceive real-world distance accurately degraded after immersion in a virtual environment? In a computer-generated world where texture and

resolution differ from the real world, it is possible that such an environment affects the ability to perceive distance accurately upon exiting the VE.

In order to answer these questions, smooth pursuit parameters, perceptual distance estimation, horizontal eye movements, and relative comfort level will be measured before and after immersion in four different display formats.

# II. METHODS

## A. SUBJECTS

Forty participants were used in this experiment. Twenty-eight men and twelve women ranging in age from 18 to 65 years (average age of 24.6 years with a standard deviation of 8.76 years). Subjects were either active-duty military students at the Defense Language Institute or the Naval Postgraduate School (NPS) in Monterey, CA, or civilians associated with NPS. The length of each subject's participation was approximately 1.5 hours. None of the participants were compensated for their participation and an informed consent form was obtained from each subject.

## B. PROCEDURE

A mixed design was used for this experiment. Each subject was randomly assigned to one of four display formats: no exposure (control condition), CRT, three-panel display and a HMD. The three-panel and HMD groups were immersed within a virtual-reality driving simulation, while the CRT group played a video game. A battery of tests (SSQ, depth perception, smooth pursuit, and optokinetic nystagmus) was administered before and after a 25-minute treatment exposure. The dependent variables were eye movement patterns (Cartesian coordinates of the eye sampled at 60 Hz) for the smooth pursuit and nystagmus tasks, distance estimation for the depth perception task, and a four-point rating scale for the SSQ.

## C. APPARATUS

The nystagmus and smooth pursuit tasks were conducted with the ETL-400 Remote Eye Tracking Laboratory from ISCAN Inc. Cambridge, MA (Razdan and Kielar, 1988). This laboratory included an IBM clone computer with a Pentium processor and 16MB of RAM, a VGA graphics adapter and monitor for basic system operation, and an eye imaging camera with optics and IR illumination from ISCAN Inc. The ISCAN Raw Eye Movement Data Acquisition and the ISCAN Point of Regard Data Acquisition software were used to collect the data, which was sampled at 60 Hz.

The stimuli for the both tasks were generated using the VisionWorks™ system with version 3 of the software from Vision Research Graphics, Inc., Durham, NH (Swift, Panish, and Hippensteele, 1997). Stimulus presentation and response collection were controlled by a VisionWorks computer graphics system (Vision Research Graphics, Inc., Durham New Hampshire; Swift, Panish and Hippensteele, 1997). Stimuli were presented on a linearized Eizo Flexscan FX-E7 monitor with resolution of 640x480 pixels (nystagmus task) and 1280x1024 (smooth pursuit task), frame rate of 60 Hz (nystagmus task) and 120 Hz (smooth pursuit task), and maximum luminance of 100 cd/m$^2$.

For the smooth pursuit task, observers viewed the screen from a distance of 1.03 meters, with their heads positioned in a chin rest. The stimulus consisted of a small circle (the target) 3mm (0.1669 degrees) in diameter moving across the computer screen. The target was stationary in the center of the screen for 1.8 seconds, then stepped to one side.

The target then moved at a constant speed in the direction opposite to the step. Four speeds, 10, 20, 30, and 36 degrees/sec were employed. The size of the step was adjusted for each velocity such that the target returned to the center of the screen 150 milliseconds after the onset of target motion. Each subject viewed all eight patterns (four velocities and two directions), with the order counterbalanced across subjects.

The participant viewed the optokinetic nystagmus stimulus, which consisted of a sinusoidal grating, on a Virtual Research V8 head-mounted display. Each subject viewed the grating at four velocities: 5, 12, 18 and 25 degrees/sec from a seated position.

During the perceptual distance-matching task, the subject was asked to judge the absolute distance to a target and then set to the distance of a matching target 180 degrees to the observer (adjusted by the experimenter) to be at an equal distance. This task took place in the hallway of an  academic building, and a green plastic cup eight inches high and five inches in diameter was used as the target. Each subject performed two trials with actual distances of 16 ft 10 inches and 33 ft 10 inches.

The Simulator Sickness Questionnaire (SSQ) was used to measure subjective comfort level (Appendix). The SSQ is comprised of 16 symptoms rated on a four-point scale, with "none," "mild," "moderate," and "severe," each represented respectively by values from zero to three (Kennedy, Lane, Berbaum and Lilienthal, 1993). It is recognized that the intervals between each rating are not necessarily equal, nor are all symptoms equally debilitating.

## D. TREATMENT ENVIRONMENTS

The CRT group played a Sega Saturn video game (Nights™ into Dream) on a JVC-27 inch Television Screen. The participants were seated approximately 1m from the screen and had a 29 degree FOV.

Both the three-panel and HMD groups were immersed in a virtual environment developed by an NPS graduate student in the Computer Science Department (Lawson, 1998). The participants were passengers in a car on a trip through a virtual town and the surrounding countryside. The computer used to generated the virtual environment was a SGI Onyx RE-2 workstation. The workstation was equipped with an Infinite Reality graphics board, 128Mb of two-way interleaved main memory, 4Mb of texture memory, 1Mb of secondary unified instruction/data cache and four 194 IP25 MHz MIPS R10000 processors.

The three-panel display consisted of three Mitsubishi Model VS5071, 40-inch, rear-projection screens set in a semi-circular configuration. The three screens were approximately 1 meter from the participant, providing the user with a 132 degree FOV. The update rate for the three-panel display was 24 frames per second (fps) (Lawson, 1998). In order for the participant to be able to change his virtual head position and thus what he could see, a BG Systems FlyBox with an integrated joystick was used.

The HMD used in this experiment was a Virtual Research V8 head-mounted display, which consisted of active-matrix LCDs with true VGA ((640x3)x480) pixel resolution and provided a FOV of approximately 60 degrees. The HMD had an update rate of 18 to 24 fps and was run in the monoscopic mode (the same input was presented to

both eyes). The tracking system used with the head-mount was the 3space Polhumus Fastrak. This electromagnetic device computed the position and orientation of a small receiver mounted on the top of the HMD as it moved through space. It provided dynamic real time, six degrees-of-freedom measurement of position (X, Y, and Z Cartesian coordinates) and orientation (yaw, pitch, and roll). The update rate of the tracker was 120 Hz with a latency of 4ms (Lawson, 1998).

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# III. DATA ANALYSIS

## A. SIMULATOR SICKNESS QUESTIONNAIRE

Almost all Simulator Sickness data is positively skewed (i.e., not normally distributed). This was true with the data collected in this experiment as well; therefore, only non-parametric tests were used. Mean and Median SSQ scores for the four conditions are shown in table 1.

| | pre | | post | |
|---|---|---|---|---|
| | **mean** | **median** | **mean** | **median** |
| **Control** | 2.244 | 0 | 2.244 | 0 |
| **CRT** | 3.366 | 0 | 5.984 | 0 |
| **3-panel** | 5.61 | 0 | 35.156 | 16.83 |
| **HMD** | 3.74 | 0 | 20.944 | 16.83 |

Table 1-Summary statistics for SSQ

Figure 1 shows the mean SSQ pre- and post-test scores for each of the four treatments.

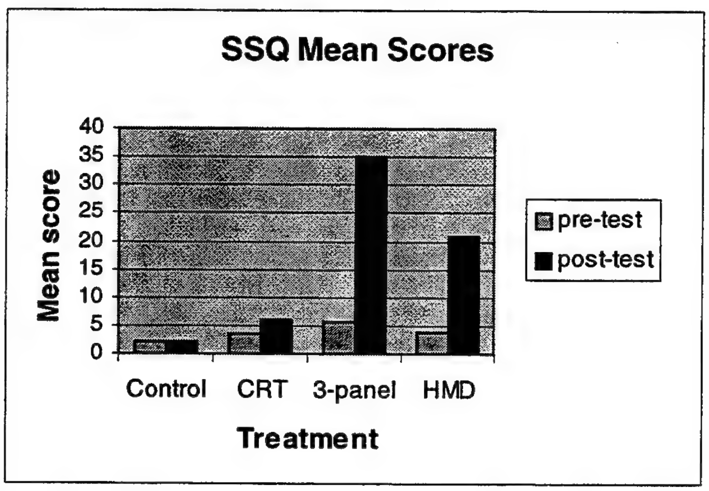


Figure 1-Mean SSQ scores

A Kruskal-Wallis test (Conover, 1999) revealed a significant difference between the treatment groups ($\chi^2(3) = 13.6822$; p=.0034). The results of a Kruskal-Wallis multiple comparison (Conover, 1999) are shown in the following table:

| **Treatments** | **p-value** |
|---|---|
| Control - CRT | 0.4056 |
| Control - 3panel | **0.0030** |
| Control - HMD | **0.0007** |
| CRT - 3panel | **0.0248** |
| CRT - HMD | **0.0065** |
| 3panel - HMD | 0.5865 |

Table 2- Kruskal-Wallis multiple comparison results

At an alpha level of .05, there is a significant difference between the control group and both the 3-panel and HMD groups, as well as between the CRT group and the 3-panel and HMD groups. These results suggest that simulator sickness as measured by the SSQ was induced by the head-mounted and 3-panel displays.

## B. DISTANCE ESTIMATION

The dependent variable for the distance-estimation data was the difference between the estimated distance from the post-test and the pre-test. The data was found to be normally distributed with equal variance, and thus parametric statistics were used in this portion of the analysis. This data is visually depicted in the following box plot and summarized in Table 3.

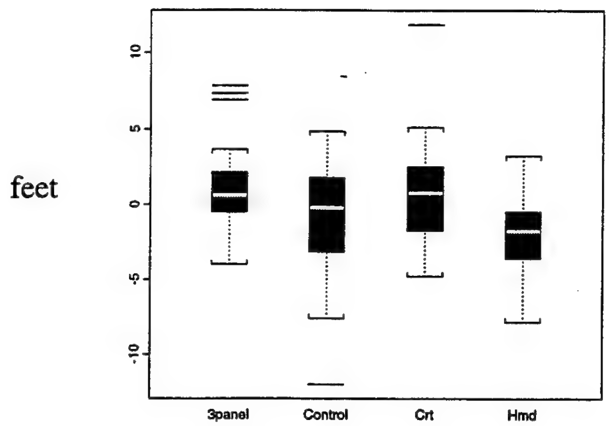


Figure 2- Box plot of distance estimation data

| Treatment | N | Mean | Median | SD | SE |
|---|---|---|---|---|---|
| Control | 20 | -0.92 | -0.22 | 3.89 | 0.87 |
| CRT | 20 | 0.75 | 0.79 | 3.74 | 0.84 |
| 3-panel | 20 | 1.26 | 0.62 | 3.14 | 0.70 |
| HMD | 20 | -1.91 | -1.75 | 2.94 | 0.66 |

Table 3-Summary statistics for distance estimation data

A 4x2 within-subject ANOVA was calculated using the model:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \gamma_{ij} + \varepsilon_{ijk} \quad \begin{array}{l} i = 1,2,3,4 \\ j = 1,2 \\ k = 1,2,\ldots 10 \end{array}$$

where $\mu$ is the overall mean, $\alpha_i$ is the effect for the treatment, $\beta_j$ is the effect for the two target distances, $\gamma_{ij}$ is the effect for the interaction, and $\varepsilon_{ijk}$ are the error terms. The $\varepsilon_{ijk}$ terms follow the usual assumptions of an ANOVA (i.e. they are independent, normally distributed and have a common variance). At an alpha level of .05 only the main effect of treatment was significant [$F(3,72)=3.55$, $p=.0185$]. Both the effect for

distance and the interaction had p-values considerably greater than .05. Tukey's method was then used to determine between which treatment groups honestly significant differences existed. Figure 3 depicts the results.

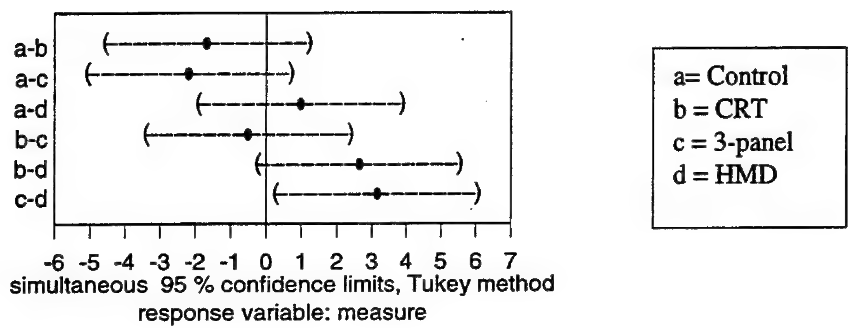


Figure 3- Tukey's method for honestly significant differences for distance estimates

The difference here lies between the 3-panel and the head-mounted display group. Using an alpha of .05 this is statistically significant, however, in the context of this study this difference is not important.

## C. SMOOTH PURSUIT

In the smooth pursuit pre- and post-tests, each subject performed eight separate trials at four different target velocities. Average eye velocity in degrees per second was then calculated for each trial. However, not all 640 data points were usable. In cases were the majority of the trials for a given subject were not usable (due to blinking during target movement or not paying attention), the subject was disregarded for this portion of

experiment. This left seven subjects in the control group and eight in each of the other three treatment groups. Within these remaining trials there were cases where one or two of the trials were not usable for the reasons cited above. Table 4 summarizes the number of usable trials for this portion of the study.

| | **Control** | **CRT** | **3-panel** | **HMD** |
|---|---|---|---|---|
| **# subjects** | 7 | 8 | 8 | 8 |
| **unusable pre-test trials** | 12 | 4 | 10 | 6 |
| **unusable post-test trials** | 5 | 6 | 6 | 10 |
| **total usable trials** | **41** | **56** | **49** | **49** |

Table 4-Usable trials for smooth pursuit task

In order to compare results across the four different target velocities, average eye-velocity divided by target velocity (gain) was used. The dependent variable for the smooth pursuit task was then calculated as the post-test value minus pre-test value. This dependent variable necessitated the use of both the pre- and post-test value, and therefore (as seen in Table 4) there were a total of 195 usable values. The dependent variable was found to be normally distributed with equal variance across conditions and thus parametric statistics were used in this portion of the analysis. This data is visually depicted in the following box plot.

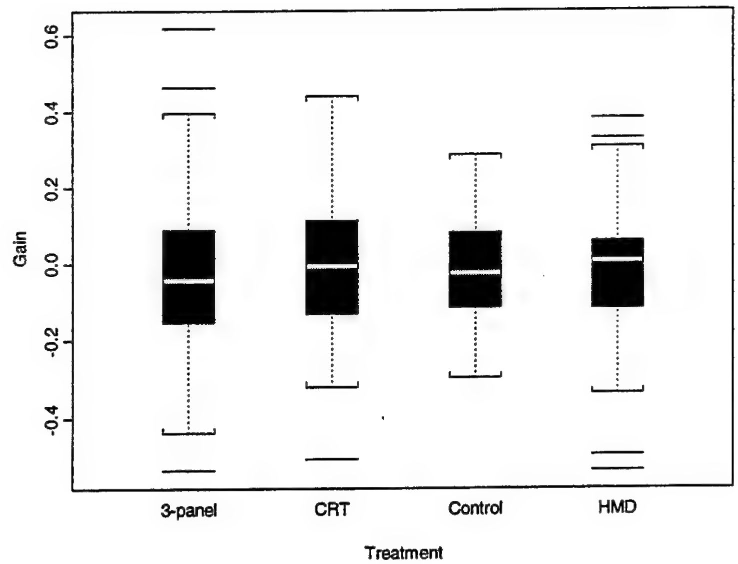


Figure 4-Smooth pursuit data across treatments

A (4 x 4) ANOVA revealed no significance in the main effect of treatment, nor in the effect for velocity, nor interaction. It is however interesting to note that average eye-velocity divided by target velocity decreased across all four velocities after HMD use; no similar pattern was found across any other groups.

## D. OPTOKINETIC NYSTAGMUS

A number of technical limitations as well as the manner in which the data were collected made meaningful analysis of the optokinetic nystagmus data virtually impossible. Figures 5 and 6 show two examples of eye movement data collected for the OKN task.

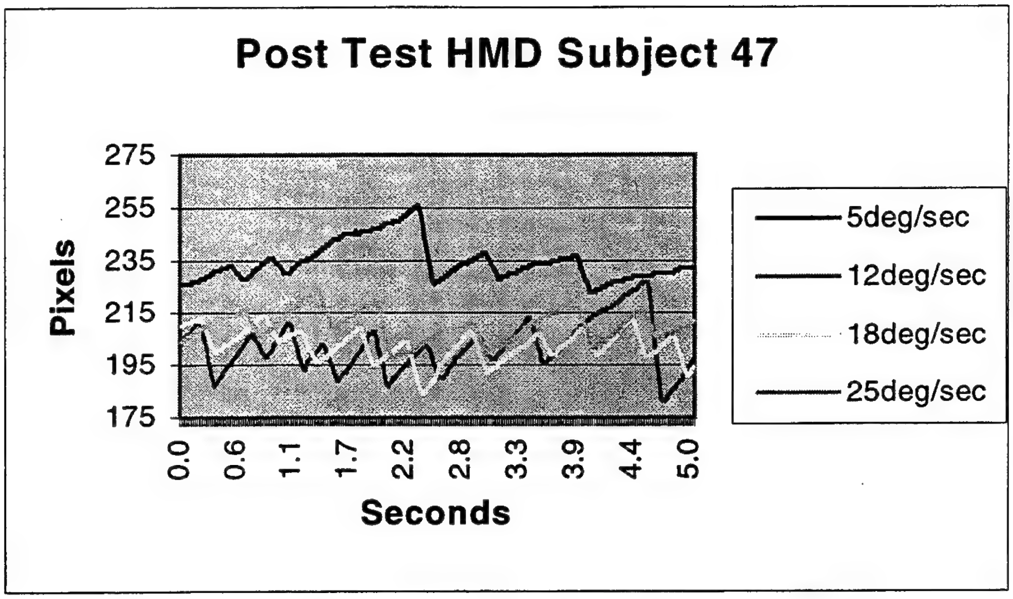


Figure 5 - Eye movement for each of the four target velocities

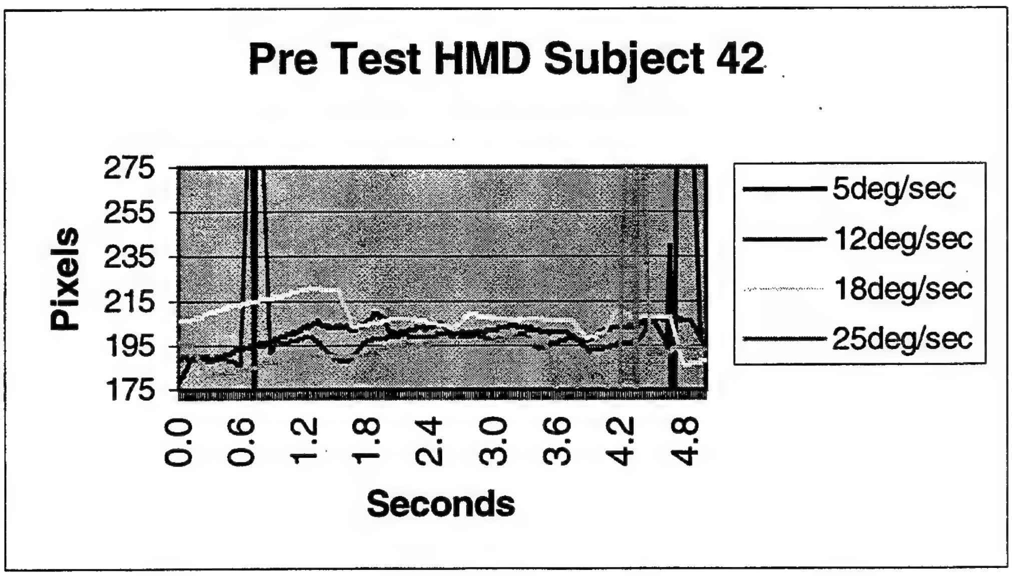


Figure 6 - Eye movement data for each of the four target velocities

Initially attempts were made to analyze the frequency and amplitude of the OKN waves in order to compare them across the four treatments. However, the standard parameter for measuring the OKN is slow-phase velocity. This is usually found using

computer software that performs pattern recognition or non-linear digital filters (Engelken, Stevens, Enderle, 1991). Because of the noise in the data, the results of manually calculating the slow-phase velocity were unusable and made the meaningful analysis of this portion of the data impossible.

# IV. DISCUSSION

## A. SIMULATOR SICKNESS QUESTIONNAIRE

Viewing the driving simulator on the 3-panel and head-mounted display clearly induced physiological discomfort. The most extreme scores came from those subjects using the 3-panel display. According to cue conflict theory, simulator sickness can be explained by a mismatch between the visual and vestibular system: when using the head-mounted display the subject moves his head and the visual scene moves, so sickness may result from the fact that the movement of the virtual environment is slightly different than that of the real world.

On the other hand, when viewing the 3-panel display the subject simply moves the joystick and the visual scene moves, and no head movement is necessary; thus, there is potentially a greater disparity between the visual and vestibular systems, which may explain the high scores.

In addition, a couple of subjects complained of flicker in their peripheral vision while viewing the 3-panel display. The point at which flicker becomes visually perceptible is known as the *flicker fusion frequency threshold* and has wide individual variability. Flicker is known to induce eye fatigue and appears to be associated with simulator sickness (Kolasinski, 1995).

Kennedy, Lane, Berbaum and Lilienthal (1993) analyzed SSQ data from 3,691 Navy simulator runs. The mean post-test SSQ score for the 3-panel display group in this

study falls within the 95th percentile on the Navy simulator scores, while the mean post-test score for the HMD group falls within the 80th percentile. It is not surprising that scores in this study were much higher as the simulation used in this study was of much lower quality than the Navy simulators. When compared to a study using a similar type of virtual environment, the mean SSQ scores are very similar. Kolasinski and Gilson (1998) found that after 20 minutes of playing a commercial video game while wearing a head-mounted display, the mean SSQ score for 40 subjects was 21.22. The range of scores found in this study were also similar to those of Kolasinski and Gilson (1998).

## B. DISTANCE ESTIMATION

There was no statistically significant difference in a subjects' ability to accurately perceive real-world distances across the four treatments in this study. It is interesting to note that previous studies on distance estimation (Witmer and Kline, 1998; Lampton, McDonald and Singer, 1995; Witmer and Sadowski, 1998) have found real-world distance perceptions are often 87 to 91 percent of actual distances. This was not the case in this study. Instead, in 74 percent of the pre-test trials, subjects actually overestimated the distance to the target. Possible explanations for this include the fact that subjects were not given any practice trials with feedback, as has been done in other studies (Lampton et al., 1995). In addition the size of the target was slightly smaller than in other studies (Witmer and Kline, 1998; Lampton et al. 1995). Witmer and Kline (1998) found that distance estimations were significantly affected by the size of the target. However,

whether the actual distance to the target was over- or underestimated, although interesting, does not affect the result of this study.

## C. SMOOTH PURSUIT

Technical limitations prevented measuring the actual smooth pursuit eye-velocity. Instead, the measure used was simply average eye velocity. The difference is that in studies of smooth pursuit, the eye is sampled at a higher frequency allowing for the removal of saccades, which are identified and removed by special computer programs. In this study, eye position data was differentiated to obtain velocity data, and average velocity was then calculated from the time the eye began to track the target until it stopped. This is a much more general measure of eye movement than pure smooth pursuit. With respect to this measure of eye movement, no effect across the four treatments was observed. These results are similar to those found by Peli (1998), who measured functional changes in binocular vision, accommodation, and resolution following 30 minutes of HMD use in both the stereoscopic and non-stereoscopic modes as compared to CRT use. Peli (1998) found no statistically significant changes in the visual system associated with these three types of displays.

The results of this study are, however, very different than those of Draper (1998), who found adaptation to the gain and phase of the Vestibular Ocular Reflex following immersion in a virtual environment. The original goal of this study was to measure other low-level vision functions (OKN and smooth pursuit) to see if similar adaptation occurred. Because of technical limitations what was actually measured was somewhat

different. Average eye-velocity, the measurement used in this study, is not strictly an involuntary eye movement like the VOR and smooth pursuit. The voluntary nature of the eye movement used in this study may be one possible explanation for the difference in results between this study and that of Draper (1998).

Another area of interest that was not examined in this study is the latency of eye movement when tracking a target. Different computer systems were used to generate the target and record eye movement. Times were not synchronized and thus there was no way to capture how long after the onset of target motion the eye began to move.

## D. OPTOKINETIC NYSTAGMUS

The optokinetic nystagmus portion of this study presented the greatest difficulty in data analysis. Eye position data from a subject exhibiting optokinetic nystagmus should exhibit a clean saw tooth form as seen in Figure 7.

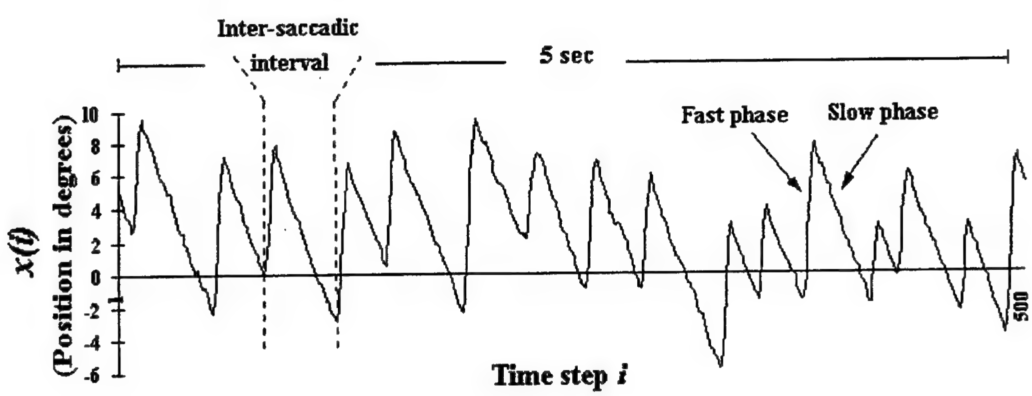


Figure 7-Typical optokinetic nystagmus (Draper, 1998)

This was not the case with the vast majority of the subjects in this study. It is therefore questionable whether or not the stimuli used actually elicited the desired response. Other studies (Robinson, 1981) have shown that the optokinetic system is maximally excited when the entire visual scene moves *en bloc*. This was not the case in this study.

Another indication as to whether or not a given stimulus is activating the optokinetic system is the presence of *circular vection,* the feeling of self-rotation (Robinson, 1981). Optokinetic nystagmus is typically elicited by placing the subject inside a circular drum with the sides covered with black and white vertical stripes. When the drum rotates, nystagmus occurs, and the subject has the sensation that *he* – not the drum – is rotating. Subjects in this study did not experience circular vection – suggesting that perhaps the optokinetic system was not excited and therefore subjects were simply making voluntary pursuit eye movements.

Another problem with the stimuli used in this study has to do with the different components of the optokinetic system. There is an initial rapid rise in slow-phase eye velocity during the first few hundred milliseconds. This velocity then gradually increases over roughly another 30 seconds to reach an asymptotic velocity close to that of the stimulus. If the visual stimulus is then removed (i.e., the subject is in the dark) *optokinetic after nystagmus* (OKAN) can be seen (Miles, 1995; Robinson, 1981; Kramer, 1998). In this study, four different stimuli velocities were used consecutively and eye movement was recorded for five seconds for each velocity. Even if the stimuli were sufficient to elicit optokinetic nystagmus, the time period in this study was not long enough to obtain the desired results. In addition, using different velocities consecutively

poses potential problems with residual eye movement. In light of these difficulties as well as others, meaningful conclusions could not be drawn from the optokinetic nystagmus portion of this study.

## E. CONCLUSIONS:

This study set out to test the hypothesis that immersion in a virtual environment causes adaptation in low-level vision functions. However, this study failed to find any changes in the ability to perceive real-world distances or to track a moving object. This may be attributed to some of the technical aspects and difficulties of this study and does not rule out the fact that these parameters may indeed be affected by exposure to Virtual Environments.

On the other hand, as with virtually every other study done on simulator sickness, this study did find statistically significant differences in comfort levels between the head-mounted display group and both the control and CRT groups, as well as between the 3-panel display, the control and CRT groups. Subjects clearly experienced physiological discomfort (as measured by the SSQ,) while viewing the driving simulator on the 3-panel and head-mounted display. Some of this discomfort may have been due to issues related simply with having worn the head-mount, such as weight and fit, heat generated by the HMD, and the tethering constraints of the head tracker. One obvious way to take this into account would have been to have used a control group that wore the HMD without any visual stimuli to see if they experienced similar discomfort. Another issue that has been raised in previous studies (Peli, 1998) is that people may be particularly sensitive to the

questions on the SSQ after having answered them in the pre-test, which may in turn lead to higher scores as people expected to, and therefore did, experience discomfort.

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# APPENDIX: SIMULATOR SICKNESS QUESTIONNAIRE

| | | | | |
|---|---|---|---|---|
| 1. General discomfort | None | Slight | Moderate | Severe |
| 2. Fatigue | None | Slight | Moderate | Severe |
| 3. Headache | None | Slight | Moderate | Severe |
| 4. Eyestrain | None | Slight | Moderate | Severe |
| 5. Difficulty Focusing | None | Slight | Moderate | Severe |
| 6. Salivation increased | None | Slight | Moderate | Severe |
| 7. Sweating | None | Slight | Moderate | Severe |
| 8. Nausea | None | Slight | Moderate | Severe |
| 9. Difficulty concentrating | None | Slight | Moderate | Severe |
| 10. Fullness of the head | None | Slight | Moderate | Severe |
| 11. Blurred vision | None | Slight | Moderate | Severe |
| 12. Dizziness/eyes open | None | Slight | Moderate | Severe |
| 13. Dizziness/eyes closed | None | Slight | Moderate | Severe |
| 14. Vertigo | None | Slight | Moderate | Severe |
| 15. Stomach Awareness* | None | Slight | Moderate | Severe |
| 16. Burping | None | Slight | Moderate | Severe |

- *Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

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